Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **25**, 293–305 (2000)

HOLOCENE DEVELOPMENT OF THE RIVER LIPPE VALLEY, GERMANY: A CASE STUDY OF ANTHROPOGENIC INFLUENCE

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Received 30 November 1997; Revised 15 November 1998; Accepted 11 May 1999

ABSTRACT

The characteristics of the Holocene valley floor of the River Lippe, Germany, are atypical for a river in central Europe. The valley floor consists of three terrace levels, which are not always clearly separated from each other. Analysis of the sediments making up the terraces indicates that they accumulated during the course of the entire Holocene, although there is insufficient information available to allow detailed determination of phases of fluvial change and stability responsible for terrace formation. Two of the terraces exist only in the lower reaches of the valley, where they converge and diverge with the third. The lowest terrace consists only of a narrow strip, running parallel to the river channel. The configuration of the valley floor may be explained by a series of anthropogenic influences. The earliest human impact probably occurred about 2000 years ago when, during their campaign against German tribes, the Romans built a towpath and may have changed the channel planform from its natural, anabranching pattern to a meandering form by building small dams on local distributary forks. Implementation of artificial meander cut-offs to improve navigation on the river began in medieval times. The morphological response to these human interventions was primarily degradational. In the 19th century, artificial lateral fill was used to narrow the channel and the towpath was renewed several times. The trace of the most recent towpath is still discernible as a narrow strip parallel to the river channel, and it constitutes the lowest terrace level. Comparison between the bankfull discharge of a 4000-year-old abandoned channel and the formative flow for the modern channel supports the premise that, prior to anthropomorphic influence, the natural planform was anabranched. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: anthropogenic influence; fluvial geomorphology; Holocene; navigation; palaeohydrology; river engineering; River Lippe

INTRODUCTION

The River Lippe is located in northwestern Germany, close to the border with the Netherlands (Figure 1). The river originates from a karstic spring at the town of Bad Lippspringe along the southern border of the Westphalian Bight and flows west to the lower Rhine at Wesel (Figure 1 and Figure 2). The lower part of the Lippe valley is situated north of the Ruhrgebiet industrial zone with Essen and Dortmund, two of the bigger cities in the region north of Cologne.

Holocene terraces have been the focus of past studies of the development of the Lippe valley floor and two of the more important terraces in the valley terrace system have been named as the Inselterrasse and the Auenterrasse (Liedtke H. and Herget J, unpublished final report for the Deutsche Forschungsgemeinschaft 1996; Herget, 1997, 1998). The Auenterrasse or Aue is the first and lowest terrace level above the river channel, that is, the floodplain. However, it is important to bear in mind that the floodplain can consist of several morphological terraces, any of which may be inundated by a flood of sufficient magnitude. The Inselterrasse is a higher, but more localized feature. Prior to the work reported here, no detailed studies of terrace morphology had been conducted.

Detailed studies have been conducted in the upper Rhine valley and the morphological evolution of the river there appears to have parallels with that of the Lippe. Studies by Bensing (1966) and Gallusser and

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Contract/grant sponsor: German Research Foundation; contract/grant number: Li86/21-1

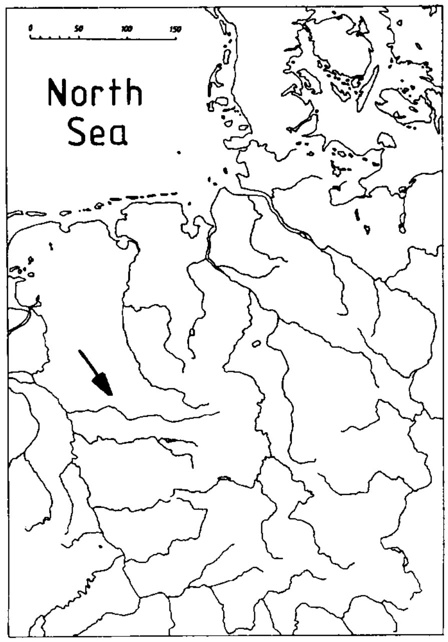

Figure 1. The location of the lower Lippe valley in northwestern Germany

Schenker (1992) have established that valley floor development in the upper Rhine valley between Basel and Mannheim has experienced strong anthropogenic influence. For example, in the 19th century several meanders in the upper Rhine valley were cut off and secondary channels were blocked to improve floodplain drainage. These river modifications led to several metres of channel incision and changed the channel planform from anabranching to meandering. Incision resulted from the concentration of the discharge into a single channel following the closure of the entrances to side channels by small dams. As a result of this incision, former river cliffs were left as terraces at several locations, including notably the Isteiner Schwelle locality, and their upper surfaces are now rarely flooded (Unterseher, 1992).

This article describes the Inselterrasse and Aue in detail and explains the Holocene development of the Lippe valley floor morphology, which is atypical for a central European river. It is shown that morphological evolution of the Lippe valley floor is a special case of anthropogenic influence that might be an interesting addition to previous studies of human impacts on palaeohydrology, channel change and valley floor development (Gregory, 1995; Brown, 1996; Kalicki, 1996).

TERRACE MORPHOLOGY

The Inselterrasse

A literal translation of the name Inselterrasse is island terrace, referring to the separation of the terrace surface into several island-like segments by abandoned channels (Udluft, 1933). The upstream portion of the Inselterrasse is a denudation terrace consisting of a single, broad level and, according to Schirmer (1995), it may be characterized as a monoplain terrace. In the lower reaches, the segregated islands of the Inselterrasse form a mosaic or loop terrace pattern (Figure 3) by Schirmer's classification. The Inselterrasse only exists as a morphological terrace between the area around Lünen (north of Dortmund) and the Lower Terraces of the Rhine at the mouth of the Lippe (Figure 2). In the headwaters, Skupin (1982, 1983) proposed that the unconformity between the sediments of the contemporary floodplain and those of the Weichselian Lower Terrace is the morphological counterpart of the Inselterrasse.

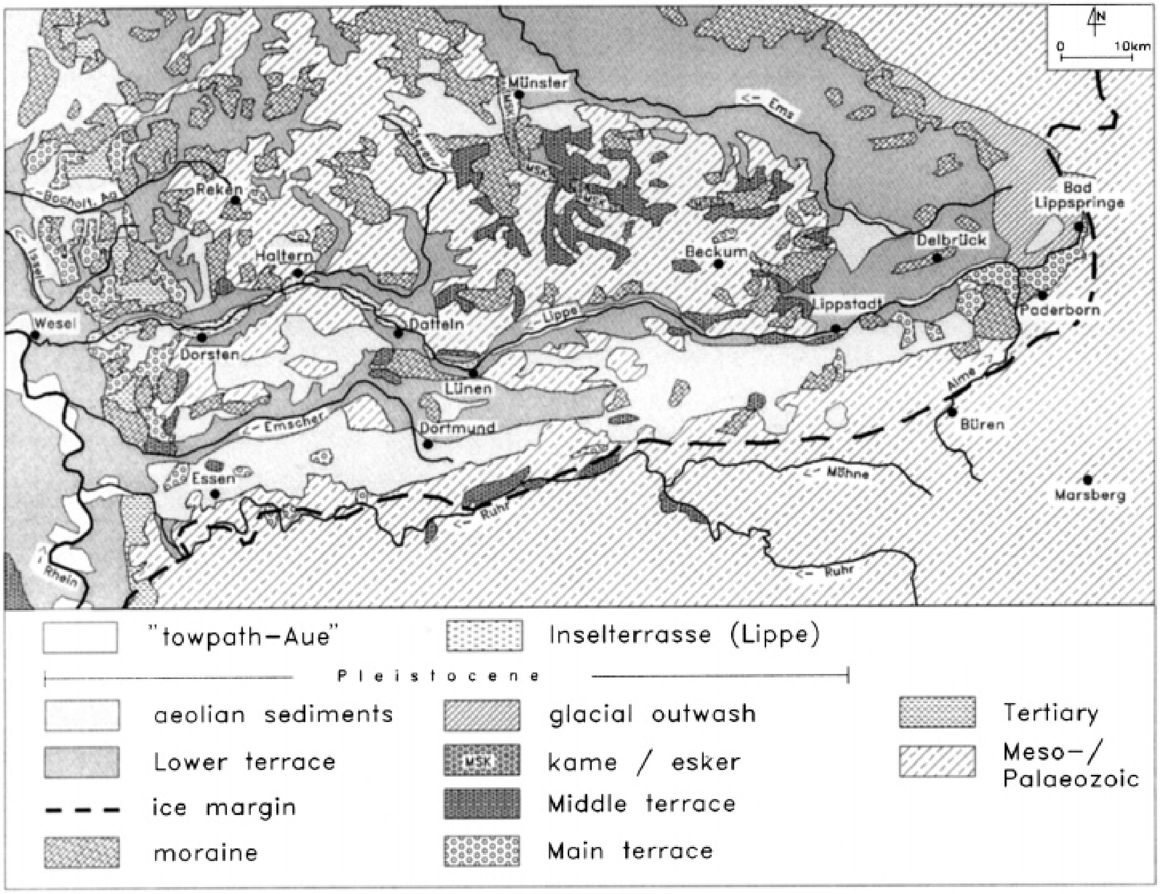

Figure 2. Simplified Quaternary sketch map of the Lippe catchment (adapted from Deutloff, 1976 and Speetzen, 1986)

The Inselterrasse and Aue diverge in the Lünen area, reaching a maximum vertical difference of 3 m around Haltern, before converging again in the lower valley. In detail the Inselterrasse can be differentiated into a higher and a lower level (Figure 3), as originally recognized by Müller (1950). The area around the gauge of Leven is suggested as type locality for this division of the Inselterrasse. In that vicinity the two Inselterrasse levels are clearly apparent, although they have a maximum difference in altitude of only 0·5 m. Owing to the local relief on the terrace surfaces, their levels are not everywhere as distinct as at Leven (Figure 2). The Aue and the lower Inselterrasse surfaces are covered by natural levees of different heights, extents and ages, making it difficult to identify the different terrace levels in places. Due to these difficulties the spatial extent of the lower level of the Inselterrasse must be regarded as uncertain.

The relief of the different terrace surfaces is further complicated by the presence of abandoned channels. The outlets of abandoned channels may be ascribed to particular terrace levels, but many channels have no clearly definable inlet. This situation results from the dynamics of sediments transported and deposited during floods. The maximum historical flood stage lies above the upper level of the Inselterrasse. Consequently, the Lippe deposits sand and silt on the floodplain, terrace surfaces and along the courses of abandoned channels. The outlets of the abandoned channels are cleared by water draining back to the river during the falling limb of the hydrograph, but the inlets are gradually filled with sediment. Consequently, at many locations only a small hollow marks a former inlet, whereas the shape of the abandoned channel is preserved at the outlet.

The Inselterrasse is located between the Weichselian Lower Terrace and the Aue. Aeolian sediments (loess, coversand and dunes) and alluvium in the Lower Terrace are of Weichselian age (115–10 ka BP). The

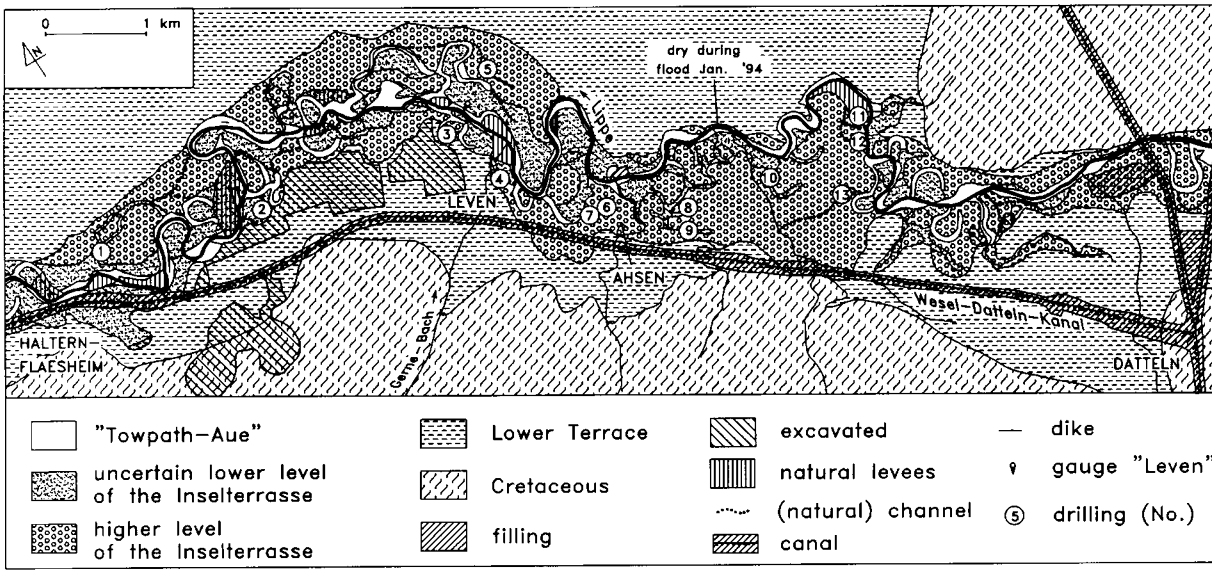

Figure 3. Holocene valley floor terraces in the lower Lippe valley between Datteln and Haltern-Flaesheim

ice margin, moraine, glacial outwash and kame/esker features belong to the Saalian ice age (300–127 ka BP), when coverage by the Scandinavian ice sheet occurred. The Middle and Main terraces were also thought to belong to the Saalian and older ice ages, but may also be interpreted as glacio-fluvial sediments deposited by a temporary drainage system at the advancing ice margin during the Saalian glaciation (Herget, 1997).

Owing to the lack of dating, only vague estimates of the age of the Inselterrasse were possible prior to this study, although most authors agree that the terrace is of Preboreal–Boreal, early Holocene age (Arnold, 1960, 1977; Braun, 1975; Skupin, 1982, 1983). In the headwaters south of Delbrück, Skupin (1982) found a peat layer with a pollen spectrum typical for the Atlantic period (7500–4500 years BP). Therefore, the underlying unconformity between the sediments of the Weichselian Lower Terrace and the floodplain sediments (which he describes as the headwater counterpart of the Inselterrasse) must be older than this. An excavation at Dorsten revealed radiocarbon ages in the cross-bedded sands of the Inselterrasse between 8100 $\pm$ 150 years BP and AD 775–980. These dates demonstrate that the accumulation of the Inselterrasse did not end prior to the Atlantic period, but has continued into historic times (E. Speetzen and K. Lanser, personal communication).

In this study, boreholes and exploratory excavations were used to investigate terrace sediments in the valley section between Datteln and Haltern-Flaesheim (Figure 3). Dating of terrace sediments and channel fills by radiocarbon and dendrochronology yielded ages that vary from older than 8000 years BC to younger than 300 years BP (Table I). Some of the channel fills are actually older than the terrace sediments (Figure 4), which might be taken to indicate that the channels contain reworked material. The difficulty with accepting this interpretation is that there are only three dates for sediments from the Inselterrasse, so that the possibility that this feature is older than indicated cannot be excluded. In this respect, speculation that the dominant period of erosion responsible for formation of the Inselterrasse occurred about 3000 years BP appears doubtful. Two dates from sediments in the Lower Terrace (Nos 1 and 5) are of Weichselian age, demonstrating that the Lower Terrace definitely predates the Inselterrasse and Aue (Figure 4).

Owing to the lack of exposures, only limited information is available concerning the stratigraphy of the valley fill. Cretaceous marl underlies the Quaternary sediments. The cross-bedded gravels and sands of the Lower Terrace form a unit that varies in thickness from 2 m to more than 20 m. These sediments were deposited by a braided River Lippe during the Weichselian. The sandy, gravel-free sediments of the Inselterrasse are cross-bedded. Typically, the sediments of the higher level of the Inselterrasse are about 2 m in thickness, locally rising to as much as 7 m. Locally, either of these sediment layers may be missing

Table I. Dates of channel fill and terrace sediments in the lower Lippe valley between Datteln and Haltern-Flaesheim (see Figure 3 for sampling locations). The radiocarbon dating was performed by BETA-Analytics Inc. (Miami), M. Geyh (Hannover) and B. Kromer (Heidelberg) using a half-life of 5568 years, a two sigma level of error and dendrochronological calibrations (regional resp. northern hemisphere scale). B. Schmidt (Cologne) examined the tree-ring ages using the north-German oak calendar

Drilling exposure No.	Terrace (sediment character)	Material (depth, cm)	Radiocarbon dating (years BP)	Calibrated age
1	Lower Terrace (terrace sediment)	Humic loam (345–375)	24 940 ± 200	–
2	Lower Inselterrasse (channel fill)	Humic loam (160–190)	2910 ± 50	1260–930 BC
3	Inselterrasse (terrace sediment)	Humic sand (255–260)	2960 ± 60	1305–1005 BC
4	Higher Inselterrasse (terrace sediment)	Wood (190)	40 ± 80	AD 1700–1955
5	Lower Terrace (terrace sediment)	Humic loam (340–370)	26 090 ± 1040	–
6	Higher Inselterrasse (channel fill)	Wood (240) Peat (300–330)	1715 ± 65 2475 ± 45	AD 250–415 765–420 BC
7	Higher Inselterrasse (fossil tree)	Fossil oak (450)	2440 ± 50	760–405 BC dendrochronology: 731–621 BC
8	Lower Inselterrasse (channel fill)	Wood (120–130)	3540 ± 50	1975–1735 BC
9	Lower Inselterrasse (channel fill)	Wood (120–125)	9100 ± 70	8230–8005 BC
10	Lower Inselterrasse (channel fill)	Humic loam (185–190)	3530 ± 70	2025–1675 BC
11	Aue (terrace sediment)	Wood (50)	560 ± 100	AD 1275–1505 AD 1595–1620
12	Higher Inselterrasse (channel fill)	Wood (210)	1870 ± 60	AD 25–265 AD 290–320
13	Higher Inselterrasse (channel fill)	Wood (225–235)	6180 ± 80	5270–4920 BC

completely. These wide fluctuations in stratigraphy and layer thickness might indicate young or recent natural vertical movements (Herget, 1997).

The Aue

In the headwaters the Aue occupies wide sections of the valley floor (Figure 2), while in the lower reaches the Aue typically consists of a narrow strip running parallel to the river channel (Udluft, 1933). However, there are exceptions to this general observation and the map of the valley floor between Datteln and Haltern-Flaesheim (Figure 3) shows that along some reaches the Aue appears to have been widened by lateral fluvial

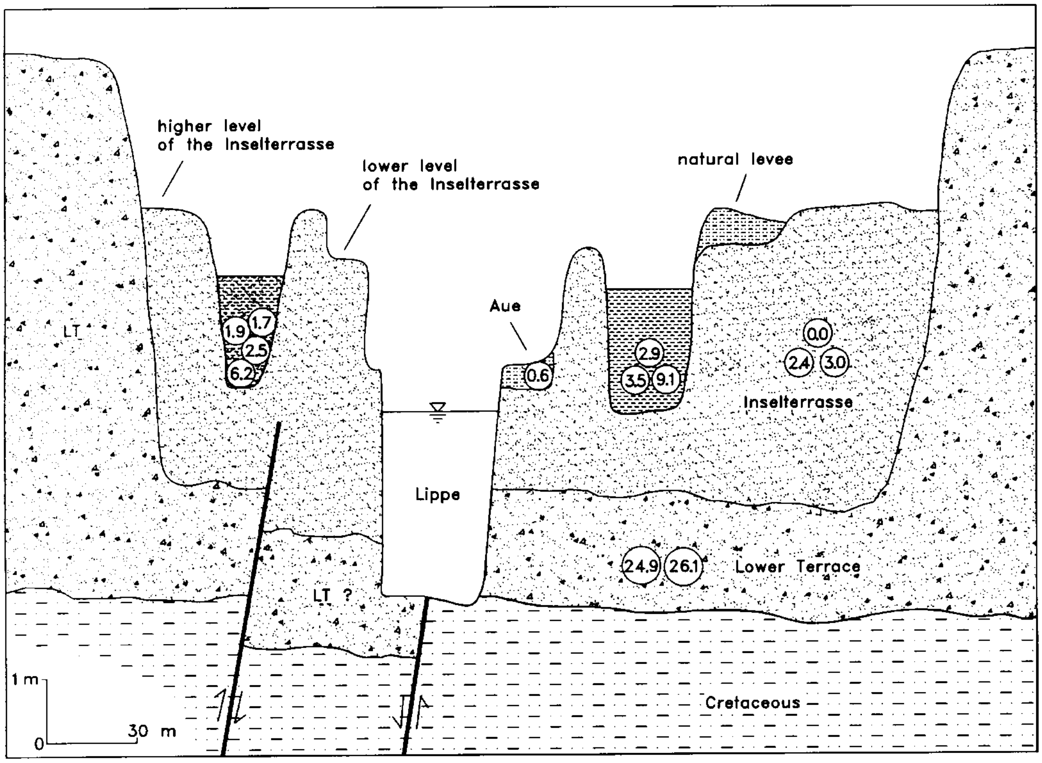

Figure 4. Schematic cross-section of the valley floor in the lower Lippe valley. The radiocarbon dates (1000 years BP) are included. The 1 km broad valley floor is shown at a smaller scale, for comparison with Figure 3

erosion during overbank events. Locally, the accumulation of sediments in natural levees may build the elevation of the Aue up to that of the lower level Inselterrasse. These contemporary sediments may still be differentiated from the sands of the Inselterrasse, however, due to their finer size and higher silt content. It would be expected that the sediments of the Aue should be younger than the Atlantic period and might include recently redeposited material. A post-Atlantic age is indeed supported by pollen analysis from the headwaters (Skupin, 1982, 1983; Hiss, 1989) and radiocarbon dating from the lower reaches (Figure 3, Nos 3 and 11). Several dated samples from the higher level of the Inselterrasse are younger than the samples from the Aue, however, which is consistent with the fact that in historical times even the higher level of the Inselterrasse was frequently flooded (Krakhecken, 1939).

During and after a flood event in January 1994, an extensive area of the floodplain was mapped (Herget, 1997). As indicated in Figure 3, one segment of the Aue was above the flood level while large areas of the lower level of the Inselterrasse were flooded. Geomorphological mapping of the valley floor confirmed that there is no possibility of differentiating the Holocene terraces in the lower Lippe valley simply by comparing the stratigraphy or levels of the terrace surfaces. A relative differentiation of the terraces based on field mapping is possible though, on the basis of sharp terrace edges with heights up to 1·5 m.

Based on a review of the literature, field mapping, sediment sampling and dating investigations it is possible to summarize the characteristics of the Holocene floor of the Lippe valley as follows:

- the Inselterrasse only exists in the lower Lippe valley, west of Lünen;
- the sediments of the Inselterrasse and the fills of the abandoned channels accumulated during the entire Holocene have a variety of dates;

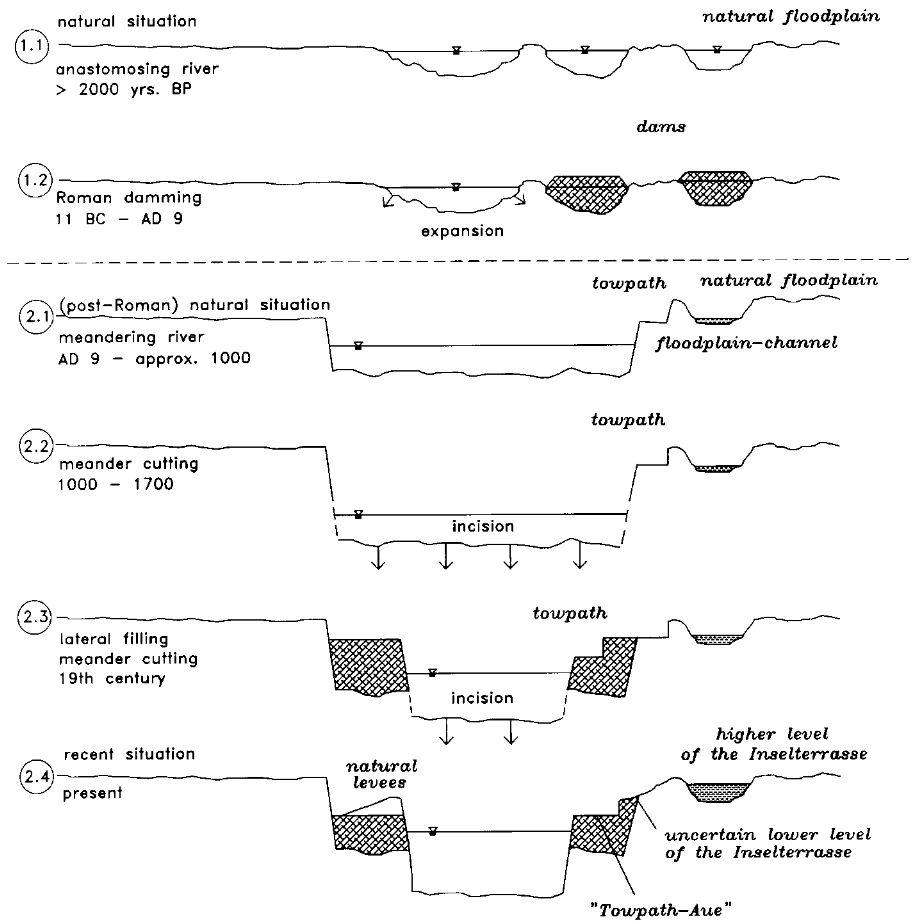

Figure 5. Conceptual development of the Holocene terraces in the lower Lippe valley

- in some reaches the Inselterrasse consists of two levels, although these are not always clearly separated from one another;
- the height difference between the Inselterrasse and the Aue diverges and converges;
- in the lower reaches the Aue consists typically only of a small strip parallel to the river channel;
- segments of the Aue lie above flood level, whereas sections of the Inselterrasse are periodically flooded. In historical times, the Inselterrasse was frequently flooded.

These characteristics, which are atypical for a central European river (see, for example, Schirmer, 1995) form the basis for a qualitative explanation of the Holocene development of the valley floor. There is insufficient information available to allow detailed reconstruction of the phases of fluvial activity and stability or to support direct comparison with other river catchments in Europe (Schirmer, 1995; Starkel, 1996). However, the quoted radiocarbon dates of Speetzen and Lanser (personal communication) from the excavation at Dorsten make it clear that the sediments of the terraces and abandoned channel fills must have accumulated during the entire Holocene.

HOLOCENE DEVELOPMENT OF THE VALLEY FLOOR

Two conceptual models may be advanced to account for development of the valley floor during the Holocene and explain the generation of its atypical features through morphological response to anthropogenic influence

(Figure 5). The first model (Figure 5, 1) assumes that, prior to human influence, the natural planform of the River Lippe was anabranching and cites Roman dams as the first human intervention in the fluvial system. The second model (Figure 5, 2) assumes that the natural, prehistoric planform was meandering, in which case human modification began during medieval times.

Conceptual Model 1

Pre-historic conditions. According to this model, the Lippe was naturally an anabranching river with its discharge distributed between several, individually meandering, channels (Figure 5, 1.1). Under this scenario, the valley floor consisted of a single broad level formed in easily erodible, sandy sediments. Evidence to support this scenario comes from the geographical positions of abandoned channels in the lower reaches of the Lippe valley (Figure 3) and the fact that these channels are too narrow and shallow to convey even the mean discharge of the river.

Roman times. During their campaign against German tribes, the Roman conquerors used the river for supply and transport (Eckholdt, 1980; Morel, 1987; Kühlborn, 1995). To improve navigation the Romans may have dammed secondary channels to concentrate flow in a single navigation channel (Figure 5, 1.2). This is technically feasible as only small dykes on local distributary forks would have been necessary to accomplish the desired concentration of discharge. The closed, secondary channels would gradually fill through sedimentation during floods. It is also widely accepted that the Romans built the first towpath to facilitate the movement of vessels. Any river engineering that occurred at this time must be ascribed to the Romans because the indigenous German population lacked both the capability and the desire to improve navigation. If proven, these river works, nearly 2000 years ago, would constitute some of the earliest examples of river engineering in Europe (Gregory, 1995).

Morphological response to damming of secondary channels would have been for the single navigation channel to deepen and widen until its hydraulic geometry was adjusted to the channel-forming flow, and for a meandering pattern, scaled on the new stable width, to develop (Figure 5, 1.2). Documented examples of channel pattern change from anabranching to meandering in response to anthropomorphic effects may be drawn from the valleys of the upper Rhine (Gallusser and Schenker, 1992) and the Elbe (G. Caspers, unpublished report, 1992).

There is no archaeological evidence for these activities by the Roman conquerors. This is not surprising as historical sources present no detailed information about Roman activities during their campaign, except their defeat by the German tribes (Kühlborn, 1995). Experts on the Roman archaeology of the area would not expect to find any accounts of river engineering, but express the view that such works would certainly be achievable by the Roman military (J.-S. Kühlborn, personal communication). Further light may be cast on this issue by historical and archaeological studies of Roman navigation on the Lippe, especially with regard to logistics and engineering, which are on-going at the University of Bonn, Germany (E. Bremer, personal communication).

The remainder of Conceptual Model 1 (for Mediaeval and Recent Times, is identical to Conceptual Model 2.

Conceptual Model 2

Pre-historic conditions Under this scenario, in its natural condition, the River Lippe occupied a single channel that actively meandered across the Aue, eroding into the floodplain and forming avulsions during floods. The Aue surface would have featured several small, overbank channels that carried discharge only during flood events and it is the traces of these flood channels that are preserved in the landscape (Figures 3 and Figure 5, 2.1).

Mediaeval times. Detailed historical evidence concerning works to improve navigation along the Lippe exists only from the early 19th century (Koppe, 1986; Strotkötter, 1895, 1896, 1907; Vollmer, unpublished report for the Staatliches Amt für Wasser und Abfallwirtschaft Lippstadt 1993), although it is reported that meander cut-offs were made between AD 1000 and 1700 in the area around Haltern (Strichling, 1932). However, since navigation on the river *is* documented, the existence of a towpath since Roman times is unquestionable (Figure 5, 2.1).

In the 12th century shipbuilding began at Dorsten and, from 1332, written records concerning navigation tolls were kept (Koppe, 1992). At this time it is believed that, in a sustained programme of channel improvements, several meanders were artificially cut off to shorten the navigation route, with new sections of towpath built along the straightened channels (Figure 5, 2.2). Engineering and channel alterations were concentrated in the lower course of the river (Krakhecken, 1939; Wiel, 1970; Koppe, 1992), although some meanders were also cut off in the headwaters (Vollmer, unpublished report for the Staatliches Amt für Wasser und Abfallwirtschaft Lippstadt 1993). However, owing to the stable Cretaceous marls in the valley floor of the headwater reaches, no additional towpath construction was required there. Outcrops of the marls in the channel bed also posed navigational problems and led to the construction of sluices to allow passage of vessels, especially during low flow periods.

The primary morphological response to meander cut-offs is generally though incision because of the steeper channel gradient (Lane, 1947; Biedenharn and Watson, 1997). Morphometric studies demonstrate that, in response to medieval and later meander cut-offs, the Lippe incised by as much as 3 m in a period of 100 years and indicate that incision continues today (Vollmer, unpublished report for the Staatliches Amt für Wasser und Abfallwirtschaft Lippstadt 1993) (Figure 5, 2.2).

Recent times. Meander cut-offs have continued to be constructed in recent times. Long periods of low water and the occurrence of sandbars in the naturally broad, shallow river channel have always been problems for navigation. To deal with these problems, and allow the passage of larger vessels, schemes have been invoked to increase water depths and suppress bar formation by narrowing the cross-section. These schemes typically involve the use of sediment dredged from the bed and the natural levees to laterally constrict and narrow the channel (Vollmer, 1993) (Figure 5, 2.3). Construction of new towpaths along straightened and in-filled reaches in the lower course has led directly to formation of a terrace feature that might be termed the 'towpath-Aue' (Figure 5, 2.4).

Primary morphological response to artificial narrowing is occurring through continued incision that has increased the vertical separation of the mean low water plane and the floodplain (Figure 5, 2.3). However, in places incision has uncovered resistant outcrops of Cretaceous marls, necessitating construction of further sluices. These outcrops have prevented headcut migration upstream and this, coupled with the fact that since the 19th century navigation has been much more intensive in the lower reaches than in the headwaters, has led to a concentration of incision in the lower course. Overbank erosion during floods has occurred at some locations, resulting in the towpath being locally expanded through erosion of the higher terrace scarps. More generally though, during floods the river is continuing to build natural levees and a terrace level (the higher level of the Inselterrasse) between the incised channel/Aue system and the Weichselian Lower Terrace (Figure 5, 2.4). In practice, natural levees, abandoned channels and old river cliff scars on the floodplain make it difficult to identify the different terraces.

Morphological interpretation

Based on these models of Holocene development, the morphology of the valley floor and its terraces may be interpreted as follows.

- The higher level of the Inselterrasse originates from the action of natural geomorphic processes initiated prior to human intervention in the fluvial system. It continues to evolve today under the natural action of floods.
- The lower level of the Inselterrasse developed initially during medieval times through morphological response, in the form of incision, to multiple meander cut-offs, and through engineering construction and replacement of towpaths.
- The Aue has developed during recent times through renewed incision, triggered by additional meander cut-offs, coupled with artificial narrowing of the wide, natural channel and reconstruction of the towpath at a lower elevation. Terrace-forming processes are not yet complete and the Aue is still developing as a narrow strip parallel to the river channel. The variable height of the historical towpath (the younger sections of which are at lower elevations) explains the lack of continuity of the Aue at an elevation above current flood levels. Based on its origin, the lowest terrace level could be termed the 'towpath-Aue'.

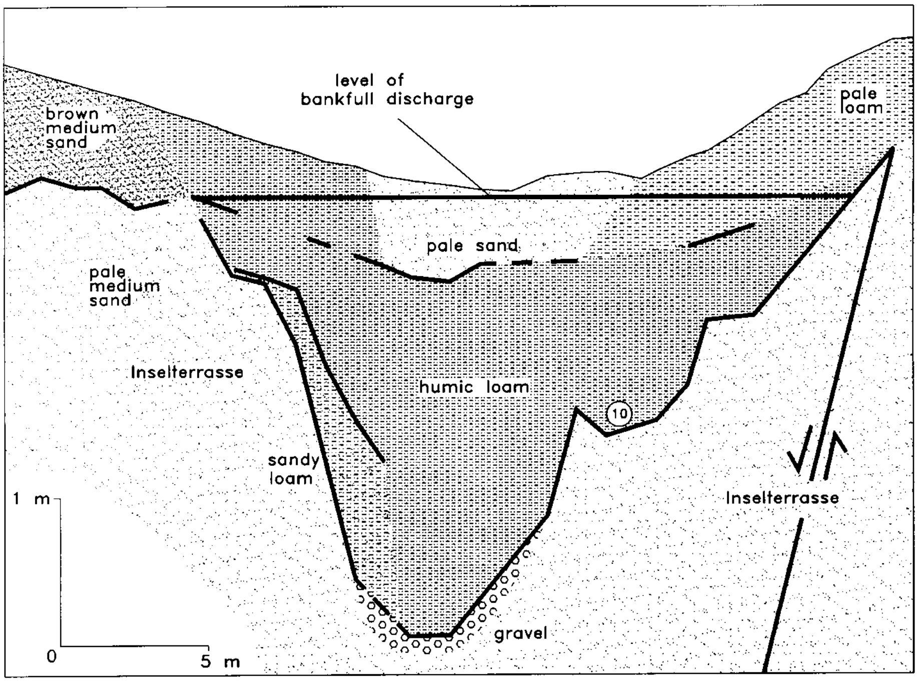

Figure 6. Cross-section of the abandoned channel at location No. 10 (see Figure 3)

- Convergence of the levels of the Inselterrase and Aue into a single, natural floodplain as the Lippe approaches its confluence with the Rhine is explained by the fact that the receiving stream has been unaffected by navigation improvements and morphological responses in the Lippe system.
- In the headwaters, incision in response to anthropomorphic influences is limited because navigation has historically been less intense and resistant outcrops have prevented upstream migration of headcuts initiated in the lower course. As a result, the Inselterrasse does not exist in the headwaters and it is, in fact, incorrect to view the unconformity between the sediments of the Lower Terrace and the floodplain as the counterpart to the Inselterrasse (cf. Skupin, 1982). Also, owing to the presence of Cretaceous marls in the valley floor, towpath reconstruction has been unnecessary in the headwaters and this explains why the Aue is extensive and the recent, narrow 'towpath-Aue' is absent.

PALAEOGEOMORPHIC INTERPRETATION OF THE NATURAL CHANNEL FORM

To decide which of the conceptual models should be accepted, it is necessary to determine whether, prior to human influence, the natural river pattern was anabranching or meandering. To address this issue the dimensions of an ancient, abandoned channel were compared to the formative discharge for the modern river. The objective was to estimate whether the conveyance capacity of the abandoned channel was sufficient to carry the channel-forming flow in a single channel. If this is the case it may be concluded that the ancient, natural river pattern was meandering. Otherwise, the pattern must have been anabranching, because more than one channel was active at the same time. An important assumption underlying this reasoning is that the flow regime of the period concerned was roughly similar to that of the modern river.

A study site was selected, at location No. 10, based on the age of the channel fill, to ensure that anthropogenic influences could definitely be excluded. Owing to technical problems with the drilling equipment and a high groundwater level (creating the risk of contamination) the sample used for radiocarbon dating could not be taken at the deepest part of the channel fill. Instead, carbon was collected from higher sections of the profile, resulting in a date of 2025 to 1675 BC. Probably, abandonment of the buried channel occurred somewhat earlier than indicated by the radiocarbon dating. On this basis the ancient channel was probably abandoned prior to 4000 years BP. The age of the fill means that the site meets the assumption regarding similarity of ancient and modern fluvial regimes as there are known to be no significant differences between the palaeohydrology for this period and the modern fluvial regime in northwestern Germany (Klostermann, 1992; Starkel, 1996).

At this location the channel fill (humic loam) could clearly be distinguished from the sands of the Inselterrasse and the dimensions of the buried channel were determined from inspection of the borehole logs (Figure 6). The ancient channel was found to be about 23 m wide and 2·8 m deep, with a cross-sectional area of 26 m^2 and a wetted perimeter of 29·5 m.

The velocity–area method and Manning formula (Morisawa, 1985) were used to estimate the bankfull discharge, Q_b, of the abandoned channel from:

$$Q_b = vA_b \tag{1}$$

$$v = R^{2/3}S^{1/2}n^{-1} \tag{2}$$

where v = mean velocity, A_b = cross-sectional area, R = hydraulic radius, S = channel slope and n = Manning roughness coefficient. The slope of the ancient channel could not be estimated from the borehole logs and, with the lack of any other available information, it was approximated by the slope of the modern channel. This is given as about 0·19 per mil, by Vollmer (unpublished report of the Lipperverband 1995). The roughness coefficient, n, was taken to be 0·04 based on a table in Morisawa (1985). This value represents a natural, clean, sinuous river channel with some pools and riffles, which is probably a fair description of the ancient channel. Substituting these data into Equation 1 yields a bankfull mean velocity, $v = 0{\cdot}32$ m s^{-1} and entering this value into Equation 2 indicates a bankfull discharge, $Q_b = 8{\cdot}3$ m^3 s^{-1}.

Ideally, the bankfull discharge of the ancient channel should be compared to that of the modern channel to check for similarities and differences. However, the modern channel cannot be compared to the ancient channel because it is heavily incised. It is generally accepted that the return period of bankfull discharge in stable alluvial channels is typically in the range of one to two years. (Leopold *et al.*, 1964; Gregory and Walling, 1973; Williams, 1978; Knighton, 1998). Hence, the two-year flood may be compared to the bankfull discharge of the abandoned channel. Williams (1978) points out that there are many exceptions to the rule of thumb that the return period for bankfull flow is two years, but as a first approximation for comparative purposes it might be acceptable.

According to Vollmer (unpublished report of the Lipperverband 1995), the two-year flood for the modern river is about 160 m^3 s^{-1}, which is nearly 20 times the estimated bankfull discharge of the ancient abandoned channel. Even given the gross assumptions and approximations underlying the calculations involved, it may be concluded that the formative flow was almost certainly conveyed in more than one channel 4000 years BP and that the channel pattern at that time was likely to be anabranching.

CONCLUSIONS

Studies of the morphology of the terraces of the Lippe valley have produced new insights concerning Holocene development of the valley floor. Intensive field studies of the valley floor have been performed for the first time, supporting a detailed description of the morphology and extent of the terraces. It is demonstrated that the incised channel and terrace surfaces that characterize the floor of the Lippe valley have developed during the entire course of the Holocene, but that they are not comparable with those in other river

valleys in central Europe. This is the case because their development has been driven by morphological process–response to the unique sequence of anthropogenic influences experienced by this river system. Weaknesses in the detailed studies reported here centre on the limited age data for the sediments of the Inselterrasse and lack of chronological information on the fluvial phases of change and stability involved in Holocene development of the valley floor. Further studies are required to address these weaknesses.

Two possible conceptual models are proposed to explain development of the channel and terrace systems during the Holocene. The first model differs from the second only in that it proposes that the predisturbance planform of the river was anabranching and that about 2000 years ago planform metamorphosis from anabranching to meandering occurred in response to damming of secondary channels by Roman engineers. Investigation of a buried channel that was abandoned by the River Lippe about 4000 years BP revealed that the bankfull discharge of this natural, predisturbance channel is 20 times smaller than the formative discharge for the modern river (represented by the two-year flood). Based on this finding, it may be concluded that the natural channel pattern of the Lippe was probably anabranching and Conceptual Model 1 may be tentatively accepted.

Further studies of other abandoned channels of different ages, in several sections of the Lippe valley, must be carried out to validate this finding and confirm that river metamorphosis from anabranching to meandering occurred in the Lippe valley sometime during the last 4000 years, in response to anthropomorphic influences. Until further studies have been performed the conclusion that the natural, predisturbance channel pattern in the lower Lippe was anabranching remains tentative. If this conclusion is validated, further detailed palaeogeomorphic analysis of the characteristics of the river and catchment 4000 years BP can be undertaken through application of the understanding of process–form linkages in modern fluvial systems with anabranched channels that has been established through the work of, for example, Nanson and Knighton (1996).

ACKNOWLEDGEMENTS

The author would like to thank H. Liedtke, E. Bremer, G. Eggenstein, S. Harnischmacher, J.-S. Kühlborn, K.N. Thome, H. Zepp and the anonymous reviewers for valuable discussion and comment on early drafts of this paper. Financial support for the studies reported here was kindly provided by the 'Deutsche Forschungsgemeinschaft' (German Research Foundation) (Li 86/21-1).

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